Nonlinear electron transport in normally pinched-off quantum wire

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Abstract. – Nonlinear electron transport in normally pinched-off quantum wires was studied. The wires were fabricated from AlGaAs/GaAs heterostructures with high-mobility two-dimensional electron gas by electron beam lithography and following wet etching. At certain critical source-drain voltage the samples exhibited a step rise of the conductance. The differential conductance of the open wires was noticeably lower than e^2/h as far as only part of the source-drain voltage dropped between source contact and saddle-point of the potential relief along the wire. The latter limited the electron flow injected to the wire. At high enough source-drain voltages the decrease of the differential conductance due to the real space transfer of electrons from the wire in GaAs to the doped AlGaAs layer was found. In this regime the sign of differential magnetoconductance was changed with reversing the direction of the current in the wire or the magnetic field, whet the magnetic field lies in the heterostructure plane and is directed perpendicular to the current. The dependence of the differential conductance on the magnetic field and its direction indicated that the real space transfer events were mainly mediated by the interface scattering.

Nonlinear electron transport in the one-dimensional (1D) ballistic devices has attracted much interest just after the linear conductance quantization ($G = n(2e^2/h)$, n is an integer) was revealed [1, 2]. The samples used in the experiments were the split gate devices with negatively biased gates, which produced a narrow constriction in the two-dimensional electron gas (2DEG) formed at AlGaAs/GaAs heterojunction. It was well realized both theoretically [3, 4] and experimentally [5–7] that in nonlinear regime near half-plateau structures in the differential conductance should be developed between the $n(2e^2/h)$ plateaus when the external
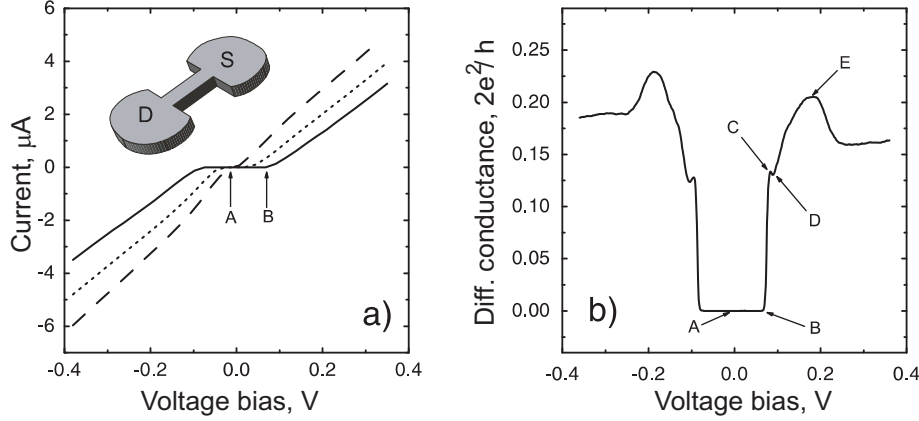
Fig. 1 – a) I-V characteristics of the quantum wires with different lithographic width (dashed curve - $0.54\mu m$, dotted curve - $0.52\mu m$, solid curve - $0.5\mu m$). Insert shows the schematic draw of the samples used in the studies. b) The differential conductance versus the voltage bias for the sample with lithographic width $0.5\mu m$. In the absence of the voltage bias ($V_{SD} = 0$) our sample is pinched-off (point "A"). The step rise of the differential conductance takes place at the critical voltage bias V_C (point "B"). Points C, D and E are discussed in the text.

voltage V_{SD} applied across the constriction is comparable to the 1D sub-band energy spacing. More generally, the exact value of the differential conductance of half-plateaus is determined by the potential distribution along the constriction and number of the 1D sub-bands involved into the electron transfer processes between contacts [8,9]. It was predicted also [10] that when $V_{SD} > E_F$, with E_F being the Fermi energy in the source (emitter) contact, the negative differential conductance could appear due to a decrease of the probability for an electron to transmit through the constriction. However this effect was not apparently observed in the quantum constrictions for V_{SD} as high as few tens of mV [5,8,11].

In this work the nonlinear electron transport through the relatively long quantum wires without gates was investigated. The wires were fabricated from AlGaAs/GaAs heterostructure with high mobility 2DEG by electron beam lithography and following wet etching. The sample arrangement is shown schematically in the insert to fig. 1a. Two-dimensional reservoirs ("S" and "D" in fig. 1a) serve as contacts to the wire. Without voltage bias V_{SD} (or source-drain voltage) applied between contacts all the wires studied were pinched off and had zero conductance since the full electron depletion in the wire by the built-in surface potential. At a certain critical voltage bias V_C the samples exhibited a step-like rise in the conductance. The similar behaviour was observed in Ref. [8] on the split-gate devices initially pinched-off by the gate voltage. Under applied voltage V_{SD} higher than V_C, the current was determined by the electron flow injected to the wire through one-dimensional sub-bands at the saddle-point located close to the source contact. In contrast to the previous studies, we extended source-drain voltage range up to the value as large as 0.4 V without sample destroy and found that at high enough voltages the real space transfer of electrons occurs from the wire in the GaAs well to the doped AlGaAs layer. This process affects significantly the electron transport through the wire. In this regime the sign of differential magnetoconductance was changed with reversing the direction of the in-2DEG-plane magnetic field transverse to the current or the current flow direction in the wire.

The quantum wires of presented studies are narrow constrictions (mesa structures) with
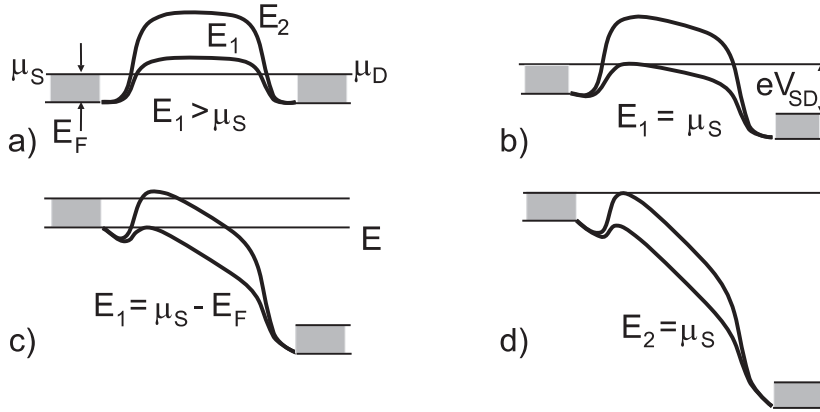
Fig. 2 – Schematic view of the 1D energy diagram along the quantum wire with contacts. The relative position of the conduction band bottom in the contacts and the bottom of the first and the second sub-bands in the wire are shown for different voltage bias. E_1 and E_2 denote the maxima of the potential barrier for the 1st and 2nd sub-bands respectively. (a) - no source-drain voltage is applied (this corresponds to point A in fig. 1b); (b) - $V_{SD} = V_C$, the bottom of the first sub-band coincides with the Fermi energy in the emitter (point B in fig. 1b); (c) - the bottom of the first sub-band coincides with the bottom of the conduction band in the emitter (point C in fig. 1b); (d)- the bottom of the second sub-band becomes lower than the Fermi energy in the emitter (point D in fig. 1b).

the length of approximately $0.8\mu m$ and the width of approximately $0.4\mu m$ fabricated by E-beam lithography and following wet etching of the GaAs/GaAlAs heterostructure with high-mobility 2DEG. The starting GaAs/GaAlAs heterostructure has the 2DEG at 100 nm beneath the surface (electron mobility is $1.4 \cdot 10^6$ $cm^2 V^{-1} s^{-1}$ at $T = 4.2$ K which corresponds to 9 μm transport electron mean free path, and the electron density - $3.1 \cdot 10^{11}$ cm^{-2} without illumination). The 2DEG is separated from the 50 nm thick Si-doped ($8 \cdot 10^{17}$ cm^{-3}) AlGaAs layer by the undoped 25 nm thick spacer AlGaAs layer.

The real width of the constrictions differed from the lithographic width since the wet etching was used. For example, the sample with lithographic width of $0.54\mu m$ had the real width of about $0.4\mu m$. Below we refer to the lithographic width when comparing different samples.

Figure 1a shows the current-voltage (I-V) characteristics for the samples with nominal lithographic widths of $0.50\mu m$, $0.52\mu m$ and $0.54\mu m$ at 4.2 K. Increasing bias voltage induced a stepwise increase of the differential conductance $G = \partial I/\partial V$ from zero to an approximately constant value G_0 (various for all samples) at a certain critical voltage V_C. We determined V_C as the voltage when the current through the sample became equal to 10 nA. The critical voltage V_C increases strongly with decreasing of the lithographic width of the wire.

The differential conductance versus voltage bias for the sample with lithographic width $0.5\mu m$ is shown in fig. 1b. The data are similar for all the samples and were acquired by the standard lock-in technique. One can see the local maximum (marked by "C" in fig. 1b) close to the critical voltage V_C. At higher voltages the differential conductance reaches the maximum (point "E" on the fig. 1b) with $G \approx 0.2(2e^2/h)$, and then falls down to the approximately constant value $G \approx 0.15(2e^2/h)$.

The main features of the I-V characteristics can be understood using the simple 1D model of the conduction band, shown in fig. 2. Without the bias voltage the maximum of the ground

sub-band bottom lies above the Fermi level in the 2D contacts (fig. 2a). The inter sub-band energy can be estimated taking into account that the constriction is strongly depleted with electrons and therefore the electric potential is produced by the positive background charge of impurities in the doped AlGaAs layer. Thus the second derivative of the potential, which determines the inter sub-band energy, is estimated as $\phi'' \sim 4\pi N_D/\epsilon_L$, where N_D is the donor concentration in the AlGaAs layer, ϵ_L is the lattice dielectric constant. In such a way the inter sub-band energy is estimated as about 10 meV.

With further increase of the source-drain voltage the barrier for the first 1D sub-band is lowered. When the applied voltage is equal to a critical value V_C, the highest point (saddle point) of this barrier coincides with the Fermi energy in the source. At this moment a step-like rise of the differential conductance must be observed (fig. 2b) at zero temperature, if the tunnelling processes are not taken into account.

Under the voltage above V_C, the saddle point is located close to the source and electrons are injected through this point into the wire where the electric field is as high as about 1 kV/cm. The electron transit time through the wire is about 10^{-12} s which is slightly more than optical phonons emission time. This argues that electrons transit the wire near ballistically.

Under this condition the differential conductance of the structure is determined by the sum of the partial conductances due to the 1D sub-bands. The partial differential conductance through the open sub-band channel $G_n = L_n(2e^2/h)$ is determined by the leverage factor L_n which is defined as $L_n = V_n/V_{SD}$, where V_n is the part of the source-drain voltage which drops between the source and the top of the barrier (a saddle point of the potential relief) of the n-th sub-band [8,9]. In general the factor L_n depends on the external voltage bias: $L_n = f(V_{SD})$. When the applied voltage is increased the saddle point position goes to the source. Hence the differential conductance should decrease with V_{SD}. As the voltage bias is further increased the top of the barrier for the first 1D sub-band goes to the bottom of the conductance band in the source 2DEG (fig. 2c), and the electron flow through the first sub-band reaches its saturation. Correspondingly the differential conductance due to this partial current goes to zero. The same happens with the electron flows through the higher sub-bands. As an example, fig. 2d shows the situation where the second sub-band barrier top intersects the Fermi level E_F.

Thus, the partial differential conductance G_n for each sub-band behaves with the applied voltage V_{SD} as follows. It is very small when $V_{SD} < (V_C)_n$, at $V_{SD} = (V_C)_n$ the conductance increases sharply to the value $G_n = L_n(2e^2/h)$ and then decreases up to zero. $(V_C)_n$ here is the critical voltage V_C for the n-th subband. The total differential conductance is a much more complicated function of V_{SD}. We believe that the local maximum observed slightly above V_C in fig. 1b is just the first local maximum, which should appear as described above. The local maximums of the higher order were not resolved on our samples.

Figure 3a illustrates by arrow 2 how the electrons injected through the saddle point travel along the constriction. It is obvious that if V_{SD} is high enough, the injected electrons can acquire the energy from the driving electric field which exceeds the height of the barrier separated the bound states in the GaAs well and states in the AlGaAs. For $Al_{0.24}Ga_{0.76}As$ this barrier height is about 0.2 V. In this case the real space transfer of electrons from the GaAs quantum channel into the AlGaAs layer is possible.

In the highly doped AlGaAs layer, the electron scattering is much stronger than in the GaAs quantum well due to presence of charged impurities and imperfections. Hence the electron transfer to the AlGaAs layer results in the scattering of the injected electrons and in the increase of the source-drain voltage fraction dropped between the saddle point and the drain. As the result, the L_n factor diminishes. This explains the differential conductance decrease with the V_{SD} voltage after the broad maximum shown in fig. 1b. At higher voltages the differential conductance only slightly depends on V_{SD}.
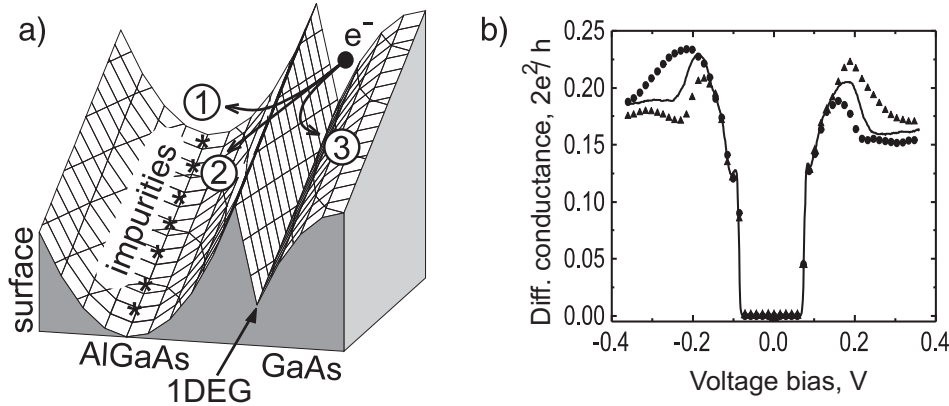
Fig. 3 – a) Schematic profile of the conduction band bottom in the heterostructure under applying a high voltage bias ($> 0.2\ V$). Arrow 2 shows schematically the ballistic trajectory of injected electrons in the wire without magnetic field. Arrows 1 and 3 show the same but with the magnetic field present. The injected electrons are forced against the interface, when the magnetic field directed down, and deflected in the opposite direction, when the magnetic field sign is reversed. b) The differential conductance versus the voltage bias for the sample with lithographic width $0.5\mu m$ in the absence (solid curve) and in the presence of the magnetic field. The magnetic field is directed perpendicular to the current, in plane of the 2DEG. For dashed and dotted curves the magnetic field is directed in the opposite directions.

The magnetic field effect on the electron transport in nonlinear regime allowed us to clarify the mechanism of the real space transfer process. It depends on the direction of magnetic field when magnetic field vector **B** lies in the plain of the 2DEG and is directed normally to the current. This is illustrated in fig. 3b where the dependence of the differential conductance versus the voltage bias is shown for three cases: (*i*) the magnetic field is absent (solid curve); (*ii*) the vector **B**, the current vector **j** and the outer normal vector **n** to the sample surface form the left-handed system (triangles); and (*iii*) the vector **B** is opposed to that in the previous case (circles). The change of the magnetoresistance sign with the change of the magnetic field or current direction was observed when the source-drain voltage is so high that the real space transfer of electrons from the quantum wire to the AlGaAs layer becomes feasible.

The similar odd magnetoresistance effect was observed previously by Sakaki [12] in the case of the diffusive electron transport along an asymmetrical quantum well under linear transport conditions. It was explained by the change of the effective scattering rate by charged impurities located near the AlGaAs/GaAs interface with the magnetic field shifted electrons closer to or farther from the interface.

At low voltages ($V_{SD} < 0.13\ V$) only positive magnetoresistance was found.

The observed decreasing of the differential conductance at high applied voltage and its behaviour with magnetic field can be easy understood if we suggest that the electron transitions from the quantum wire to the AlGaAs layer are caused by the GaAs/AlGaAs interface scattering. The transition probability is proportional to the matrix element $|<\chi_n|U|\psi>|^2$ where U is a scattering potential localized near the interface, ψ is a wave function extended over the AlGaAs layer, χ_n is the wave function of electrons confined in the wire. The wave function $\chi_n(y, z)$, y and z being the transverse coordinates, is determined by the potential confining electrons in the lateral direction (y) and by the triangular well produced by the built-in electric field F_s normal to the interface (z direction). The magnetic field affects the

wave function in the normal direction. It changes the confining field by adding the Lorenz force: $F = F_s + \hbar Bk(x)/(mc)$, where $k(x)$ is the wave vector describing the electron motion along the wire. If the Lorenz force is directed toward the interface, the subband bottoms in the wire are shifted up and the wave function is localized closer to the interface. Both these factors enhance the electron transitions from the wire to the AlGaAs layer. As a result the magnetic field decreases the conductance. The magnetic field of opposite direction suppresses the real space transfer of electrons giving rise to the conductance increase. The value of the magnetoresistive effect is determined by the ratio of the Lorenz force to eF_s. The wave vector k can be estimated as $k \sim (2meV_{\mathrm{sd}})^{1/2}/\hbar$. Under the experimental conditions $V_{\mathrm{sd}} \sim 0.2\ V$ and $B \sim 8\ T$, this estimation shows that the equivalent confining electric field is about $2 \cdot 10^5\ V/cm$, which is comparable with the built-in electric field. Hence the magnetic field essentially affects the transport of ballistic electrons in the wire and gives rise to the strong magnetoresistive effect.

In conclusion, we have investigated the nonlinear electron transport through relatively long quantum wire which is normally pinched-off by the build-in surface potential. The current transport is observed when the driving (drain-source) voltage exceeds a critical value V_C above which the quantum wire becomes open. At high enough applied voltage, comparable with the conduction band offset between GaAs and AlGaAs, the real space transfer of electrons from the quantum wire into the highly doped AlGaAs layer becomes important. The magnetic field, that lies in the heterostructure plane and is directed transverse to the wire, results in a high magnetoresistive effect. It is caused by the magnetic field influence on the real space transfer processes. The dependence of the magnetoresistance sign on the direction of magnetic field or current in the wire indicates that electrons real space transfer events are mainly due to the interface scattering.

REFERENCES

[1]   VAN WEES B. J., VAN HOUTEN H., *et al.*, *Phys. Rev. Lett.*, **60** (1988) 848
[2]   WHARAM D. A., THORTON T. J., *et al.*, *J. Phys.: C*, **51** (1988) L209
[3]   GLAZMAN L. I., KHAETSKII A. V., *Europhys. Lett.*, **9** (1989) 263
[4]   V'YURKOV V. V., FEDIRKO V. A., *Sov. Phys. Semicond.*, **23** (1989) 1061
[5]   PATEL N. K., MARTIN-MORENO L., ET AL, *J. Phys.: Condens. Matter*, **2** (1990) 7247
[6]   PATEL N. K., NICHOLLS J. T., *et al.*, *Phys. Rev. B*, **44** (1991) 10973
[7]   PATEL N. K., NICHOLLS J. T., *et al.*, *Phys. Rev. B*, **44** (1991) 13549
[8]   KOUWENHOVEN L. P., VAN WEES B. J., *et al.*, *Phys. Rev. B*, **39** (1989) 8040
[9]   MARTIN-MORENO L., NICHOLLS J. T., *et al.*, *J. Phys.: Condens. Matter*, **4** (1992) 1323
[10]   KELLY M. J., *J. Phys.: Condens. Matter*, **1** (1989) 7643
[11]   BROWN R. J., KELLY M. J., *et al.*, *J. Phys.: Condens. Matter*, **1** (1989) 6285
[12]   SAKAKI H., OHNO H., *et al.*, *Physica B*, **117 & 118** (1983) 703